# The Relationship among Stride Parameters, Joint Angles, and Trajectories of the Body Parts during High-Heeled Walking of Woman

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## ABSTRACT

**Objective:** This paper analyzes the changes on stride parameters, joint angles, and trajectories of the body parts due to high heels during walking and explains the causal relationship between the changes and high heels. **Background:** This study aims to indicate the comprehensive gait changes by high heels on the whole body for women wearing high heels and researchers interested in high-heeled walking. **Method:** The experiment was designed in which two different shoe heel heights were used for walking (1cm, 9.8cm), and twelve women participated in the test. In the experiment, 35 points on the body were tracked to extract the stride parameters, joint angles, and trajectories of the body parts. **Results:** Double support time increased, but stride length decreased in high-heeled walking. The knee inflexed more at stance phase and the spine rotation became more severe. The trajectories of the pelvis, the trunk and the head presented outstanding fluctuations in the vertical direction. **Conclusion:** The double support time and the spine rotation were changed to compensate instability by high heels. Reduced range of motion of the ankle joint influenced on the stride length, the knee flexion, and fluctuations of the body parts. **Application:** This study can provide an insight of the gait changes by high heels through the entire body.

Keywords: High-heeled walking, Gait analysis, Heel height and posture, Trajectory of the body parts

## 1. Introduction

Wearing high heels is a natural behavior for women in modern life in order to have a more attractive appearance. Researchers in various fields have studied gait changes in normal walking due to high heels. Merrifield found in stride parameters of gait that high-heeled females are apt to walk with shorter steps and strides to compensate for a less stable position of the body's center of gravity (Merrifield, 1971). It is presented that the step length of high-heel walking is shorter than that of both flat-heel and sneaker walking (Sato and Takahashi, 1991). A study conducted by Gehlsen et al. also reported that stride length and stride time decreases with increasing heel height because of the reduced average range of the knee joint angle during the swing phase of walking (Gehlsen et al., 1986). These studies show the influence of high heels on stride parameters.

There is another approach, focused on the torque or the joint angles of the body parts. It is observed that maximum

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knee flexion is smaller at the swing phase and greater at the stance phase with high heels (Ucanok and Peterson, 2006). Kerrigan et al. investigated torques about the ankle and knee joints for woman wearing high heels. In that study, it turned out that the peak ankle torque in the sagittal plane significantly decreases with high heels, but the varus knee torque in the coronal plane increases (Kerrigan et al., 1998). Similarly, there is a study showing that knee moments of the medial side and ankle moments of the plantar flexion side significantly increase with high-heeled walking, which may cause accidents resulting in musculoskeletal injuries, or an increased risk in slipping (Yu et al., 2010). In addition, it is found by Lee et al. that the lumbar flexion angle reduces as the heel height increases which makes a more unstable posture and creates additional compressive forces in the lower lumbar spine (Lee et al., 2001).

Regarding experiments for muscle activity using Electromyographic (EMG) signals related to shoe heel height, Stefanyshyn et al. indicated that the EMG activities of the soleus and rectus femoris show a gradually increased response with increased heel height (Stefanyshyn et al., 2000). Moreover, it was shown that muscle responses to fatigue using EMG are different between wearers of flat heels and high heels. According to a study by Gefen et al., peroneus longus and gastrocnemius lateralis muscles are more vulnerable to fatigue especially for regular wearers of high-heeled shoes (Gefen et al., 2002). There is a study by Iunes et al. showing that excessive wearing of high-heeled shoes leads to shortening of the calf musculature so frequent high heel wearers feel uncomfortable with flat shoes (Iunes et al., 2008). Speksnijder et al., meanwhile, demonstrated that wearing high heels causes increased peak pressure and pressure time integral under the central forefoot, medial forefoot, and hallux, which resulted in load shifting from the heel region toward the toe region (Speksnijder et al., 2005). However, in a study by Eisenhardt et al., flat shoes show a higher peak pressure than high heel shoes with different percentages for the stance phase at which peak pressures occurred (Eisenhardt et al., 1996).

As many studies have indicated, high heels considerably influence the gait pattern, including stride parameters, joint movement, muscle activation, and feet pressure. The previous studies were mainly focused on identifying symptoms caused by high heels or analyzing the risk of injury using EMG signals or kinetic data of the ankle, knee or spine. The purpose of this paper is to find gait characteristics in high-heeled walking through the entire body using kinematic data.

As shown in the study by Morris, point-light videos of women wearing high heels are rated as more feminine and attractive than the women wearing flat shoes (Morris et al., 2012). The study indicates that people can intuitively recognize gait changes due to high heels by watching the trajectories of the body parts. From this point of view, in this paper, trajectories of the body parts throughout the entire body are analyzed in addition to stride parameters and joint angles during high-heeled walking (Park et al., 2012). From the result, an analysis is given of the differences between high-heeled and flat-heeled walking on the trajectories and stride parameters, and which characteristics induce the more attractive gait style of a female in high heels. Finally, the causal relationship among the changes due to wearing high heels is explained. This study would be useful for designing shoes to create different gait styles such as an attractive gait style for women and unique gait patterns for characters in performance.

# 2. Method

## 2.1 Subjects

Twelve female participants age 20 to 30 years who were healthy enough to have an independent gait participated in this study. The gait difference by age is negligible particularly for young and healthy people (Perry, 1992). Average height and weight of the participants were 159.98±4.30cm and 50.16±3.01kg, respectively. The body mass index (BMI) of each participant was in the range between 17.5% and 22.1% which is approximate in the range of the standard body weight (18.5~23%), so it is considered that the effect of obesity is insignificant in the experiment. The average leg length of the participants was 84.58±1.98cm, of which the deviation was considered to be small enough to ignore the effect of leg length on stride parameters. The shoe size was restricted to 235mm in order to utilize the same shoes for all participants for avoiding the effect of shoe differences in the experiment. Therefore, only the women who have the shoe size of 235mm were asked to participate in the experiments. In addition, all subjects had prior experience wearing high heel shoes with various heel heights and types of shoes.

### 2.2 Instrumentation

Walking trials were conducted on a 7m walkway with the middle 5m designated for data collection. A Vicon motion capture system of 12 cameras (Vicon T160 Camera, Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data in 100Hz using 35 reflective markers (19 on the upper body and head, 16 on the lower limb referenced by Plug-in-Gait Marker Set) consisting of 14mm spheres. Two types of women's fashion shoes, which were different in shape and heel height (flat shoes of a 1cm heel and high-heeled shoes of a 9.8cm heel), were applied in this study (Figure 1).

**Figure 1.** Two experimental shoes and placement of attached markers on the body

### 2.3 Procedures

All experiments were conducted at the motion capture studio in the Advanced Institutes of Convergence Technology. Before the experiments, all participants received a detailed description of the study and signed a consent form approved by the Institutional Review Board of Seoul National University. In addition, the participants had trained for adjusting to the different shoe heights each time the shoe conditions were changed until they feel comfortable with the changed shoes. Normally, the walking speed of gait is expressed in cadence and it is well known that the average cadence for a woman is 118 steps/min (Inman et al., 1981; Perry, 1992). Thus, each subject was asked to walk three times at a cadence of 118 steps/min hearing the sound of a metronome for each shoe condition to disregard the effects of speed difference. Among the three trials of walking, one trial which has the cadence closest to 118 steps/min was chosen for each person and shoe condition.

### 2.4 Data process and statistical analysis

Stride parameters, joint angles, and the body parts trajectories were obtained for the flat shoes and high heels. The data was organized in 3 seconds starting at heel strike, which includes about 3 cycles at 118 steps/min cadence. The trajectory data was recalculated through the trend-line to set up an identical starting point. Vicon Nexus v1.5.2 and Polygon v.3.5 software (Vicon software, 2011) were used to analyze the gait characteristics and process the kinematic data. The average, standard deviation (SD) and maximum/minimum points were calculated for the twelve subjects. The statistical analysis on the data was performed using Matlab. Significant level of *p*-Value was set to less than 0.05 in paired t-Test.

## 3. Result and Discussion

### 3.1 The gait changes by high heels

The changes in stride parameters and joint angles due to high heels are shown by Bar graphs in Figure 2. The stride ratio, which is the stride length divided by stride time, decreased because of the reduced stride length (Figure 2(a)). The support time ratio, which is double support time divided by single support time, was 1.5 times greater with high heels than flat shoes (Figure 2(b)). Therefore, walking speed decreases because of the short stride length and the long support time, even though the cadence is identical. The results imply that high-heeled gait has less efficient locomotion than flat shoe gait.

The ankle dorsi/plantar-flexion had completely different averages and a reduced range of motion (Figure 2(c)). The knee flexion had a higher peak at the stance phase (Figure 2(d)), but a lower peak at the swing phase with high heels (Figure 2(e)). Hip flexion shows the slightly extended range of motion with high heels. It is considered that the reduced range of ankle motion and the bent knee joint at stance phase restrict the moment to move forward, so hip flexion tends to be increased by compensating for the restriction of the ankle and knee.

Spine tilt in sagittal plane and rotation about vertical axis became greater during high-heeled gait (Figure 2(f)). The results on the knee flexion and spine angle are consistent with the study by Opila et al. (Opila et al., 1988). Thus, the influence of high heels is distinct on not only the joint angles of the lower limbs, but also the upper body, which finally changes the entire kinematics and kinetics of the body.

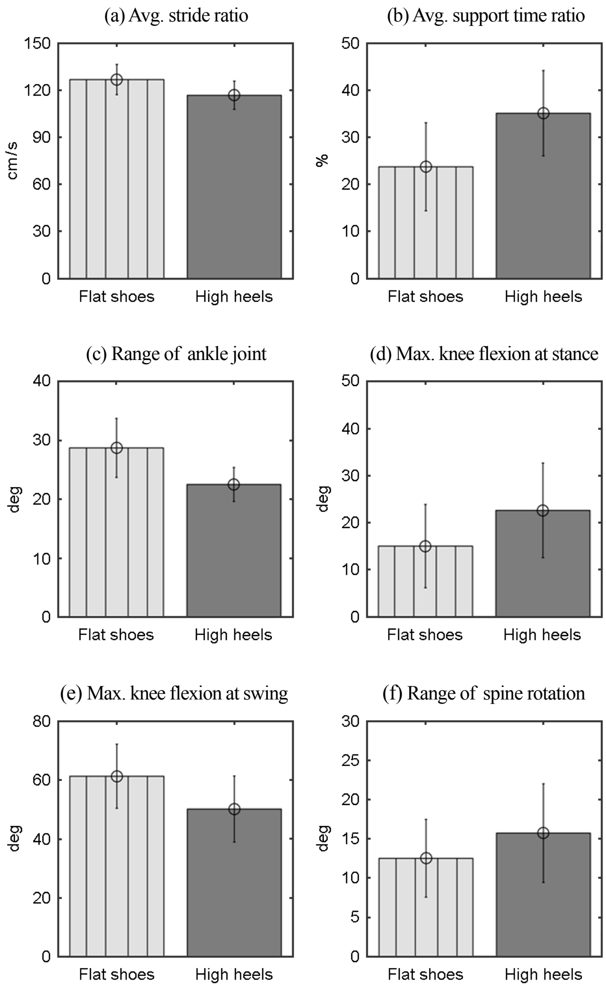


**Figure 2.** Changes in stride parameters and joint angles due to high heels: the striped bar and solid bar mean averages and the line with a circle means standard deviation for twelve subjects. Stride ratio means (stride length)/(stride time)×100. Support time ratio means (double support time)/(single support time)×100.

The trajectories of different body parts are plotted in Figure 3, where the anterior-posterior and vertical directions are denoted by X and Z respectively. Along the Y-axis (lateral trajectory) no specific changes were found so it has not been included in the figure.

The ankle trajectory in the Z-axis shows narrower motion with high heels (Figure 3(a)) which would result from the reduced range of the ankle movement at stance phase and the less bent knee joint at swing phase. On the other hand, the knee trajectory had the opposite results to the ankle (Figure 3(b)) because of the more bent knee joint at stance phase and the wide hip flexion. The pelvis trajectory in Z-axis showed the greater fluctuation at high-heeled gait (Figure 3(c)), and the effect was observed continuously in the upper body and head trajectories (Figure 3(d)). The fluctuation of the pelvis trajectory in Z-axis would be considered as the vertical movement of the body during walking. In high-heeled walking, the forward movement is restricted as shown in Figure 2(a), (b), (c) and (d), but the vertical movement becomes relatively severe. The result implies the combination of forward locomotion and upper body fluctuation requires more energy in high heeled gait than that of flat shoe gait. The ankle trajectory in X-axis indicated the slightly reduced movement with high heels (Figure 3(e)). A unique feature appeared at the knee along the X-axis, which had a different temporal peak point (Figure 3(f)). The feature is regarded as the result from rollover changes by high heels (Hansen et al, 2004), however it should be studied more for clarification. Along the Y-axis, no specific changes were found. All the statistical data are presented in Table 1.

### 3.2 The causal relationship among the changes

The changes by high heels in stride parameter, joint angle, and the body parts trajectory could be explained by two reasons.

First, the raised heel position by high heels increases the plantar-flexion of the ankle at the initial posture wearing

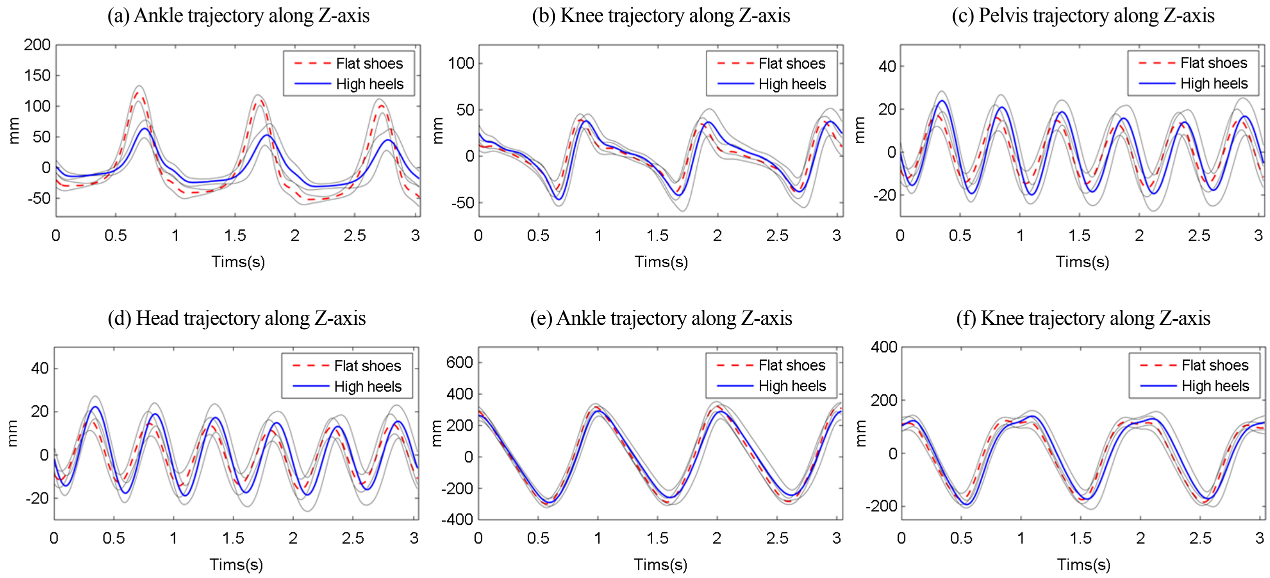


**Figure 3.** Trajectory of the body parts along Z-axis and X-axis for twelve subjects: thick red dotted or blue solid line means average and thin gray line means standard deviation

**Table 1.** Statistics of the stride parameters, joint angles, and trajectories of the body parts

| | | Average | | SD | | *t*-Test |
|---|---|---|---|---|---|---|
| | | Flat | Heels | Flat | Heels | *p*-Value |
| Stride parameters | Stride ratio (cm/s) | 126.65 | 116.63 | 9.63 | 8.99 | 0.0017 |
| | Support time ratio (%) | 23.72 | 35.08 | 9.33 | 9.04 | 0.0002 |
| Joint angles (unit: deg) | Mean of ankle dorsi/plantar | 7.88 | -17.03 | 3.76 | 4.47 | <0.0001 |
| | Range of ankle dorsi/plantar | 28.73 | 22.51 | 5.02 | 2.90 | 0.0032 |
| | Max knee flexion at stance | 15.03 | 22.60 | 8.86 | 10.06 | 0.0010 |
| | Max knee flexion at swing | 61.22 | 50.10 | 10.87 | 11.21 | <0.0001 |
| | Range of hip flexion | 45.09 | 46.80 | 2.36 | 3.08 | 0.0319 |
| | Range of spine tilt in sagittal plane | 13.79 | 16.23 | 4.05 | 3.83 | 0.0037 |
| | Range of spine rotation about vertical | 12.51 | 15.73 | 4.95 | 6.28 | 0.0007 |
| Z-axis (unit: mm) | Range of ankle trajectory | 178.98 | 102.30 | 20.88 | 16.68 | <0.0001 |
| | Range of knee trajectory | 84.10 | 98.16 | 10.31 | 15.38 | 0.0022 |
| | Range of pelvis trajectory | 37.19 | 49.27 | 8.45 | 10.24 | 0.0005 |
| | Range of neck trajectory | 37.03 | 50.30 | 8.17 | 10.15 | 0.0003 |
| | Range of head trajectory | 35.43 | 46.70 | 8.25 | 10.64 | 0.0005 |
| X-axis (unit: mm) | Range of ankle trajectory | 642.74 | 613.94 | 46.83 | 43.24 | 0.0258 |
| | Range of knee trajectory | 328.50 | 346.64 | 24.70 | 29.78 | >0.05 |

high heels. This change results in shortened plantar flexor and gastrocnemius muscles (Csapo et al., 2010), which is an uncomfortable state, particularly at stance phase to support the body's entire weight and moment. In the state, the muscles are vulnerable to fatigue (Gefen et al., 2002) and the plantar-flexion motion of the ankle is restricted (Figure 2(c)). Therefore, the knee joint is compelled to bend more, especially at a single support time to release the stiff muscles

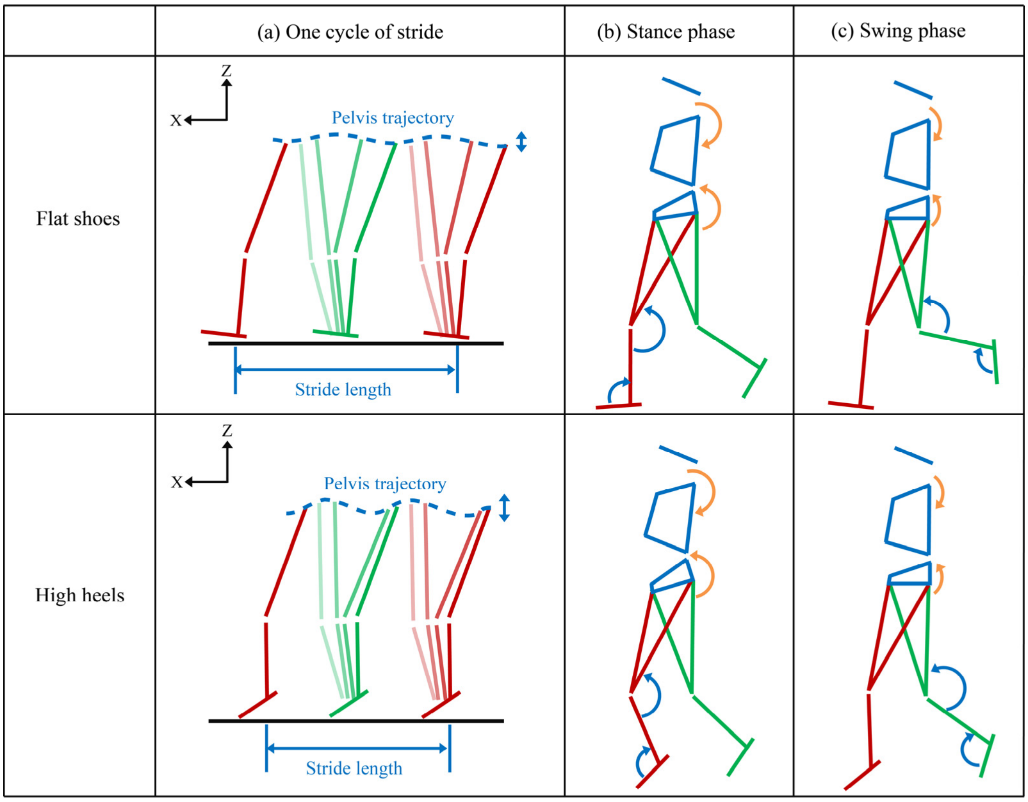


**Figure 4.** The causal relationship for the ankle, knee, pelvis, spine, and stride length

(Figure 2(d)). The bent knee joint brings the lower position of the body's center of gravity to be stable with the shorter linear distance from the ground. The decreased distance between the foot and pelvis provides the narrower range of locomotion that finally creates the shorter stride length with high heels (Figure 4(a)). Furthermore, the linear distances of the legs at a double support time and a single support time are different because of the knee bend. Therefore, the tilt in sagittal plane and vertical fluctuation of the pelvis increase in high-heeled walking. Due to the tilted pelvis, the spine tilt in the sagittal plane naturally occurs towards the opposite direction for balance (Figure 4(b)). In brief, the changed knee motion by raised heel position causes the changes in stride length, pelvis/spine tilt and vertical fluctuation of the body which generate the unstable posture.

On the other hand, the instability increases by the smaller contact region between the feet and the ground. The narrow contact region increases the shear ground reaction force (Blanchette et al., 2011), which means increasing body moments in the transverse plane. Therefore, the pelvis and spine rotation about vertical axis tend to increase consequentially compensating for the instability (Figure 2(f)). In addition, double support time becomes longer to ensure stable locomotion and balance. The change of double support time means that high-heeled walking motion automatically tends to change from dynamic walking to static walking. Static walking is the motion that has a longer double support time to ensure the period transferring the body's center of gravity from an unstable position to a more stable position for balance.

## 4. Conclusion

The aim of this study was to determine the gait changes by high heels on stride parameters, joint angles, and trajectories of the body parts and to understand the causal relationship among the changes. As mentioned in the result, many changes were found with the high-heeled gait and the casual relationship is explained by the two fundamental reasons: restricted ankle motion and instability by heels.

The trajectories of the body parts along the X-axis (anterior-posterior direction), Y-axis (lateral direction), and Z-axis (vertical direction) were analyzed to distinguish the intuitive changes in gait. The trajectories of the pelvis, the upper body and the head in the Z-axis had outstanding fluctuations with high heels. In addition, the pelvis and the spine presented the more severe tilt and rotation wearing high heels than flat shoes. The movement changes of the upper body by high heels demonstrate that people may be able to recognize the high-heeled walking intuitively by watching trunk motion only.

On the other hand, there was a noticeable difference in the trajectory of the ankle in the Z-axis, which had a much smaller range of motion with high heels. This means that the motion of the lower limbs in the sagittal plane has a contracted movement with a smaller stride length and ankle trajectory. However, the motion of the upper body has a wide movement with the more rotation and fluctuation of the trunk. These factors explain the reason why people think women wearing high heels have a gait with quick and short steps, and larger hips swaying which are considered as the more attractive gait style for women (Morris et al., 2012).

The knee joint has more flexion at the stance phase, but less flexion at the swing phase wearing high heels than with flat shoes. The changed knee movement and reduced contact areas of the feet by high heels induce the different motions of the body to rotate and fluctuate more, especially for the spine joint. The different motions eventually increase the moment of the ankle, the knee and the spine joints. Therefore, the muscles on the joints should have more strength for more stable walking.

This paper analyzed the walking data of twelve women in two different shoes. The small number of the participants and two shoe conditions would be limited to explain the generalized results. However, the average body size of the subjects participated in the experiment (height: 159.98$\pm$4.30cm, weight: 50.16$\pm$3.01kg, leg length: 84.58$\pm$1.98cm, shoe size: 235mm) correspond with the statistics of the body size in the 20 to 34 age group presented from the Korea National Statistical Office (height: 159.60$\pm$4.83cm, weight: 52.73$\pm$5.93kg, leg length: 84.01$\pm$3.51cm, feet size: 22.90$\pm$0.88mm). Thus, it is considered that the result would be valuable for female in their twenties.

From the result, it is clear that different heel heights of shoes generate different walking style. Likewise, intentional gait change is possible by wearing specially developed shoes for performance or dance. From now on, we plan to study the female and male walking under various shoe conditions such as wedge heels, platform shoes, boots, and so on. The information of walking patterns depending on different shoes could be used for shoe design, performance, and clinical purposes.

## Acknowledgements

This work was funded by grants from the Advanced Institute of Convergence Technology (Grant-#2011-P3-15).

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Date Received : 2013-02-26

Date Revised : 2013-04-12

Date Accepted : 2013-04-15